Effects of Prescribed Fire on Site Productivity: A Literature Review

Land Management Report NUMBER 66

ISSN 0702 9861

JANUARY 1990

BC
Ministry of Forests

90-03816/

Effects of Prescribed Fire on Site Productivity: A Literature Review

by
S.B. Lindeburgh

R.R.#1
Box 1979
Clearwater, B.C.
V0E 1N0

January 1990

Prepared for:
Research Branch
B.C. Ministry of Forests
Victoria, B.C.
V8W 3E7

Ministry of Forests

Canadian Cataloguing in Publication Data

Lindeburgh, S. B.
Effects of prescribed fire on site productivity

(Land management report, ISSN 0702-9861 ; no. 66)

Updates: The ecological effects of slashburning with particular reference to British Columbia / by M.C. Feller. 1982.
ISBN 0-7718-8908-9

1. Prescribed burning - British Columbia - Bibliography. 2. Fire ecology - British Columbia - Bibliography. 3. Slash (Logging) - British Columbia - Bibliography. 4. Forest productivity - British Columbia - Bibliography. I. British Columbia. Ministry of Forests. Forestry Division. Research Branch. II. Feller, M. C. (Michael Charles), 1946- . The ecological effects of slashburning with particular reference to British Columbia. III. Title. IV. Series.

Z5991.L56 1990 016.5745'2642'09711 C90-092031-9

© 1990 Province of British Columbia
Published by the
Research Branch
Ministry of Forests
31 Bastion Square
Victoria, B.C. V8W 3E7

Copies of this and other Ministry of Forests titles are available from Crown Publications Inc., 546 Yates Street, Victoria, B.C. V8W 1K8.

ABSTRACT

Slashburning, or prescribed fire, is a commonly used site preparation practice in British Columbia. The literature reviewed in this report deals primarily with the effects of prescribed fire on site productivity. Results from different studies are often difficult to compare because of the large variability among sites and inconsistent reporting.

Prescribed fire can benefit or hurt site productivity, depending on such variables as, the amount and type of slash, the fire weather indices, the timing of logging and burning, and the ecological characteristics of the site.

ACKNOWLEDGEMENTS

This report was completed as a contract with the B.C. Ministry of Forests. I would like to thank G. Still, D. Coates, and D. Meidinger for their help in the initial stages of the project; and G. Still, D. Meidinger, B. Hawkes, M. Feller, E. Hamilton, G. Hope, and M. Curran for their valuable critiques. G. Montgomery edited the manuscript. A. Baker did the word processing.

TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGEMENTS iii

1 INTRODUCTION 1

2 EFFECTS OF PRESCRIBED FIRE ON SOIL EROSION 2

2.1 Physical Properties 2

2.2 Water Repellency 2

2.3 Erosion Losses 4

3 EFFECTS OF PRESCRIBED FIRE ON PRODUCTIVITY 5

3.1 Organic Matter 5

3.2 Nutrients 6
3.2.1 Nitrogen 6
3.2.2 Sulfur 8
3.2.3 Calcium 8
3.2.4 Magnesium 9
3.2.5 Potassium 9
3.2.6 Phosphorus 10
3.2.7 Iron 10

3.3 Soil Acidity 11

3.4 Temperature 11

3.5 Post-burn Productivity 12

4 CONCLUDING COMMENTS 12

5 LITERATURE CITED 13

TABLES

1 Water repellency as a function of burning temperature and duration 3

2 Soil erosion from snowmelt overland flow 4

3 Fire Weather Index System moisture codes and forest floor data for the CWH and SBS 5

1 INTRODUCTION

In 1982, Dr. M. Feller prepared "The Ecological Effects of Slashburning with Particular Reference to British Columbia: A Literature Review" (Land Management Report No. 13). Since then, more research into the effects of prescribed fire has taken place. This project was initiated to update Feller's report. D. Coates of Skeena Forestry Consultants completed the literature search upon which this review is based.

The primary focus of this report is the ecological effects of prescribed fire, in particular, the effects on the soil resource. Articles that do not pertain to conditions found in British Columbia have generally not been included in this discussion. Inevitably, there has been some overlap of reference material between this and the Feller report.

Prescribed fire is a common site preparation method in British Columbia. It is used to meet several objectives (Feller 1982):

1. Reduction of fire hazard;
2. Facilitation of planting;
3. Provision of an environment favourable to seedling establishment and growth;
4. Reduction of brush competition or undesirable advance regeneration;
5. Elimination of disease or insect problems;
6. Improvement of aesthetics;
7. Enhancement of browse or grazing potential; and
8. Improvement of an area for use by some wildlife species, primarily ungulates.

Achieving these objectives depends on the severity of the burn. However, the potential for site degradation is also affected by fire severity. Generally, a more severe burn increases the potential for site degradation whereas a less severe burn may benefit the site by, for example, facilitating nutrient cycling (Wells *et al.* 1979; Martin 1981).

Fire severity is described by Brown and DeByle (1987) as "the total effect of fire on the ecosystem including consumption of organic material and mortality to plants and soil organisms." In some references, the term "fire intensity" is used to describe fire impact. Alexander (1982) defines it as "the energy output rate per unit length of fire front and [it] is directly related to flame size." In this report, fire severity is used in discussing the ecological effects of fire.

Burn prescriptions must meet the objectives of several concerns: silviculture, soils, water, fire, and others (Martin 1981). Because prescribed fire can have both positive and negative effects on a site, the forest manager must evaluate a fire's net effect as compared to other site preparation options.

Fire behaviour is very complex and results often appear to be contradictory (Feller 1982). Incomplete or inconsistent reporting of data often made it difficult, in this review, to compare results from different reports. For example, factors such as fire severity, fuel loading, and other site characteristics were sometimes poorly documented. The more recent reports tend to have more complete descriptions.

As well, the method of reporting results varies. One report may discuss nutrient loss from a site as a percentage of the nutrient capital in the slash and forest floor; another report may discuss the loss relative to the nutrient pool in the forest floor and mineral soil. This does not suggest there are shortcomings in these reports. It just means that readers must be aware of these differences and the potentially different conclusions that may be cited.

2 EFFECTS OF PRESCRIBED FIRE ON SOIL EROSION

Prescribed fire can modify soil physical properties and, in some instances, intensify the water repellency of a soil. In turn, these factors can increase erosion on a site.

2.1 Physical Properties

Physical properties of soil can be affected directly by slashburning (e.g., through changes in bulk density caused by the burning of organic material) and indirectly (e.g., through the exposure of mineral soil to raindrops) (Wells *et al.* 1979).

In one study, the bulk density of the surface inch (2.5 cm) of the mineral soil decreased significantly following logging, probably because of the incorporation of fine logging residue into the soil surface (DeByle and Packer 1981). After burning, the bulk density increased, likely as a result of the partial combustion of some of these fine organic materials. It continued to increase for 2-4 years before decreasing again towards logged, unburned values. For 7 years after burning, bulk densities remained below those in the forested control. Recovery seemed to be slower on south and west slopes. Tarrant (1956) found that bulk density decreased 8-11% after a low severity burn and increased 7-8% after a high severity burn.

Changes in bulk density have been inversely correlated to soil porosity (DeByle and Packer 1981). Tarrant (1956) found that a severe burn resulted in a reduction of 74 and 77% in macropore space (as compared to that in an unburned soil) in a sandy clay loam (SCL) and a pumicy sandy loam (SL), respectively. This reduced the percolation rate by over 70% in both soils. A low severity burn reduced macropore space by 26% in the pumicy SL and 58% in the SCL. In these soils, percolation rate increased by 93% in the pumicy SL and 4% in the SCL. This apparent anomaly may be due, in part, to the highly aggregated character of the surface soils. In all cases, micropore space increased.

On exposed mineral soils, aggregates can be dispersed by the impact of raindrops. Pores become clogged and there is a resultant decrease in macropore space, infiltration, and aeration (Klock and Grier 1979; Wells *et al.* 1979). Boyer and Dell (1980) suggested that erosion potential is increased by this process. Ash deposited at the soil surface and heat disruption of soil aggregates may reduce the permeability of soils to water (Woodmansee and Wallach 1981). Durgin (1985) reported that soil heating may reduce soil erodibility, particularly in well-developed forest soils, by reducing the dispersion of clay particles. However, as rain leaches through ash into well-developed soils, dispersion may be promoted and erodibility may increase.

2.2 Water Repellency

Fire-induced water repellency has the potential to increase runoff and erosion (Wells *et al.* 1979). Soil texture, the presence of organic matter, temperature gradients in the mineral soil, fire intensity, and soil water content are perhaps the most important factors influencing water repellency (DeBano 1981).

Water repellency develops as organic substances are vaporized at the soil surface and moved downward by temperature gradients (DeBano 1981). As these substances cool, they condense on mineral soil particles and become water repellent. Temperature gradients which cause this may go from 800°C at the soil surface to about 150°C at 5 cm.

Water repellency can develop in an unburned system from the mixing of partially decomposed organic matter and mineral soil, and from the deposition, in the upper soil profile, of leachates from brush and decomposing plants. Fungal growth can also produce water repellency (DeBano 1981). DeByle and Packer (1981) found that the layer in the surface organic horizon filled with fungal hyphae was very water repellent when dry in mid-summer. However, this layer does not appear to have practical hydrological significance.

Some soil textures are more prone to becoming water repellent than others. Boyer and Dell (1980) assigned water repellency hazard ratings to soil texture classes as follows:

Coarse texture	=	S, LS, medium and coarse SL	=	high hazard
Medium texture	=	L, SiL, 'light' CL, fine and very fine SL	=	medium hazard
Fine texture	=	C, CL, SiC, SiCL, SC, SCL	=	low hazard
Pumice	=	volcanic ash > 0.05 mm	=	low hazard

C = clay L = loam S = sand Si = silt

DeByle and Packer (1981) found that high clay content can prevent serious repellency even when other conditions are suitable.

The persistence of a heat-induced water repellent layer depends partly on the intensity and duration of the fire. A more intense burn can result in a higher degree of repellency or longer lasting effects (DeBano 1981). In a laboratory experiment, DeBano and Krammes (1966) collected non-wettable soils which were put through a 0.5-mm sieve and subjected to several temperatures for different time periods. The results are shown in Table 1. Note that under higher temperatures and longer durations, the non-wettable condition is reduced or destroyed.

TABLE 1. Water repellency as a function of burning temperature and duration

Duration of burning	Burning temperature °F (°C)						
	300 (149)	400 (204)	500 (260)	600 (316)	700 (371)	800 (427)	900 (482)
5 min	N	N	N	M	E	E	E
10 min	N	N	M	E	E	E	E
15 min	N	M	E	E	E	M	N
20 min	N	M	E	E	M	N	N

N - no appreciable increase in non-wettable condition.
M - appreciable increase in non-wettable condition after treatment (water droplets remain on the surface of the samples for 5-75 minutes).
E - extremely non-wettable condition after treatment (water droplets remain on the surface of the samples for longer than 75 minutes).
From DeBano and Krammes (1966).

Soils with higher water content produce less repellency (DeBano 1981) because of insufficient heating (DeByle and Packer 1981).

Repellent soils may not form on all sites. Sites may require the presence of a hydrophobic layer before burning, and burning then intensifies the repellency of the soil (DeBano and Krammes 1966), possibly by allowing the organic particles to chemically bond to the mineral particles (DeBano 1981).

In Montana, however, fire did not cause appreciable development of water repellency in the mineral soil (Jurgensen *et al.* 1981). In another Montana study, although water repellency was sometimes more prevalent, especially after intense burns, it was lost within two years (DeByle and Packer 1981). In fact, fewer mineral soils were repellent 1-2 years after burning than were repellent before burning.

In coastal British Columbia, there was no significant difference in water repellency among unburned clearcuts and forested sites (Henderson and Golding 1983). Water repellency was more prevalent on burned sites than forested sites for 1- and 2-year-old burns. There was no trend for 6-year and older burns. Repellency was more frequent after burning at the 0-4 cm depth, but there was no significant difference at other depths. On one site, increased repellency apparently caused active surface erosion. This area, with a slope of 29° and shallow soils, had been burned 2 years previously. On other sites, an increase in repellency did not appear to cause severe erosion or affect regeneration.

2.3 Erosion Losses

After burning, overland flow and soil erosion can be increased because of the reduction in soil porosity, the formation of a water-repellent layer in the soil, a breakdown in soil structure, or the removal of the protective vegetative cover and forest floor materials (Feller 1982).

Erosion losses and the associated nutrient losses after slashburning can be considerable. In Montana, DeByle and Packer (1981) carried out a study to determine the effects of clearcutting and burning on erosion associated with overland flow from snowmelt and summer storms. The authors found that most soil erosion occurred within 2 years of site treatment. Table 2 shows the soil erosion from snowmelt overland flow in one study area (with an average slope of 24%, and 1-3 cm of silt loam overlaying 30 cm of gravelly loam).

TABLE 2. Soil erosion from snowmelt overland flow

Years after burning	Winter precipitation (mm)	Erosion[a] (kg/ha)
1	305	63
2	455	188
3	430	17
7	835[b]	0

[a] No erosion was recorded from timbered control plots.
[b] This was the highest precipitation recorded over the 7-year study period.
Data taken from DeByle and Packer (1981).

Overland flow from summer storms was 5 mm during the first year after burning and produced 169 kg/ha of sediment (DeByle and Packer 1981). Precipitation during this period was 305 mm. Soil erosion decreased to approximately 20 kg/ha in the second year and no erosion occurred by the fourth year. The authors concluded that the more intense summer storms provide a much more efficient eroding force than does snowmelt runoff. Plots on steeper slopes showed a similar pattern.

In the Southern Appalachians, Van Lear and Danielovich (1988) reported that, after high severity fires on slopes of 21-43%, most of the soil movement was apparently attributable to the harvesting operation. Burning did not significantly increase sediment movement compared to that in the unburned control. During these burns, a mat of fine roots, left intact during burning, was thought to be responsible for minimizing erosion losses.

Overland flow is significantly reduced once vegetation is sufficiently established. Soil stability is improved by root reinforcement, soil moisture depletion from rainfall interception and transpiration, and regulation of snow accumulation and melt rates (Gray and Megahan 1981). Seepage flow through soils that have revegetated does not adversely affect slope stability, even on steep slopes (DeByle and Packer 1981).

On burned plots, nutrient removal in runoff water was greatest in the first year after burning because of a flush of soluble materials from the ash on the soil surface (DeByle and Packer 1981). Some nutrients may also be removed from the site by wind erosion of the ash (Woodmansee and Wallach 1981).

Merseneau and Dyrness (1972) reported that after slashburning in western Oregon, rates of soil movement increased, especially on slopes unprotected by organic debris. During the first growing season after burning, soil movement was greatest on steeper slopes, on south aspects, and in areas having little plant cover. By the second season, rapid vegetation establishment had essentially halted soil movement on all slopes except extremely stony talus areas.

Low severity fires do not generally increase soil erosion (Wells *et al.* 1979).

3 EFFECTS OF PRESCRIBED FIRE ON PRODUCTIVITY

Many site characteristics are affected by prescribed fire including organic matter, nutrients, soil acidity, and temperature. These characteristics can have direct and indirect effects on site productivity.

3.1 Organic Matter

Organic matter can affect tree establishment and growth by influencing soil temperature, type of seedbed, and the soil nutrients available for tree growth. A reduction in the depth of the organic horizons may be desirable to create plantable spots. Exposing mineral soil and blackening the soil surface can beneficially raise soil temperature, although excessively high post-burn temperatures can produce detrimental effects (Feller 1982). However, litter and duff are major sinks for calcium, copper, iron, potassium, magnesium, manganese, sodium, zinc, nitrogen, and phosphorus (Stark 1982). The removal of these nutrient sinks is potentially damaging to the site. For example,Taylor (1987) attributed much of the nutrient loss from slashburning to fine slash and forest floor consumption.

The organic horizons are also important as the medium in which ectomycorrizal root tips are concentrated (Harvey *et al.* 1986). On sites with thin forest floors, root tips may be most numerous in the surface 4 cm of the mineral soil. Slashburning should be applied with caution to minimize disturbance of these soil horizons.

Important in determining the amount of forest floor consumed in a prescribed fire are the Fire Weather Index System (FWI) moisture codes. As Table 3 shows, forest floor reduction tends to increase as the FWI moisture codes increase. These studies, carried out in the Coastal Western Hemlock (CWH) and Sub-Boreal Spruce (SBS) biogeoclimatic zones, should not be compared to each other because of other site differences.

TABLE 3. Fire Weather Index System moisture codes and forest floor data for the CWH and SBS

	Fire Weather Index System moisture codes			Forest floor	
	Fine fuel moisture code	Duff moisture code	Drought code	Average reduction (%)	Average pre-burn depth(cm)
CWH	86	19	42	24-40	10.0-14.9
CWH	89	12	215	61	12.2
CWH	82	23	295	85	16.1
SBS	86	8	335	28	8.7
SBS	83	41	513	36	10.4

Data for CWH from Beese (1986).
Data for SBS from Macadam (1987).

Slash loading also has an impact on the amount of forest floor consumption. In Oregon, duff depth reduction from burning was 36% higher with conventional logging (removal of all material greater than 20 cm in diameter x 3 m in length) than with closer utilization (removal of all material greater than 15 cm x 1.8 m or 41 cm x 0.6 m) because of the differences in fuel loading associated with the harvesting method (Little *et al.* 1982).

In a western Montana study, logging significantly increased the organic matter content in the surface 2.5 cm of the mineral soil because of mixing during harvesting operations (DeByle and Packer 1981). Burning decreased it to, or slightly below, forested conditions. Organic matter content was not significantly affected below 2.5-5 cm. Jurgensen *et al.* (1981) found similar results in Montana. In the SBS, although total carbon content in the mineral soil was slightly lower 9 months after burning than before burning (Macadam 1987), it had increased 21 months after burning to above pre-burn levels.

In a 25-year study in western Washington and Oregon, Kraemer and Hermann (1979) found that revegetation of plots had apparently replenished the organic matter lost through burning.

3.2 Nutrients

Soil nutrients are essential for tree growth. During and after slashburning, the total nutrient capital can be reduced through atmospheric losses, leaching, and erosion. The short-term availability of many nutrients may be increased by the rapid mineralization that occurs after a burn (Curran and Dunsworth 1988), and low severity burns may facilitate the cycling of some nutrients (Wells *et al.* 1979). However, high severity fires can cause nutrient deficiencies (Stark 1982). As well, the availability of nutrients can be affected by changes in soil acidity brought about by fire (Curran and Dunsworth 1988).

In the CWH zone of coastal British Columbia, Feller (1988) carried out a slashburning study with three different slash loadings of western hemlock (*Tsuga heterophylla*). Nutrient loss generally increased with slash load and could be attributed almost entirely to the greater fuel consumption that occurred with the greater slash loads.

Feller (1988) also found that nutrient loss seemed to be affected by slash type. Losses tended to decrease in the order of western redcedar (*Thuja plicata*) and yellow cypress (*Chamaecyparis nootkatensis*) > Douglas-fir (*Pseudotsuga menziesii*) > western hemlock.

In Montana, over a 2-year period after treatment, Entry *et al.* (1987) found that concentrations of nutrients which had leached through the organic horizon did not differ significantly among treatments. The treatments were clearcut and residue left, clearcut and residue removed, clearcut and residue burned, and uncut control.

It is important to note that logging alone can reduce considerably the nutrient capital of a site. Logging (the removal of wood > 7.6 cm in diameter) in a western larch (*Larix occidentalis*)/Douglas-fir stand in Montana removed about 1% of the total ecosystem calcium, iron, potassium, manganese, sodium, zinc, nitrogen, and phosphorus, and 11% of the copper (Stark 1982).

3.2.1 Nitrogen

In Idaho, logging in a mature ponderosa pine (*Pinus ponderosa*)/Douglas-fir stand removed 136 kg N/ha, which amounted to 4% of the total pool in the standing crop, litter, and soil (Clayton and Kennedy 1985). The authors stated that this should not represent an unacceptable nutrient loss over a normal timber stand rotation.

During burning, most of the nitrogen in fine forest fuels is volatilized. Very little nitrogen is lost in forms that could be returned to the soil by precipitation (DeBell and Ralston 1970; Nissley *et al.* 1980). The amount of nitrogen released into the atmosphere appears to depend on a variety of factors including fuel loading, fire severity, and duff depth. Little and Ohmann (1988) found nitrogen loss to be directly proportional to the amount of forest floor consumed.

A low severity slashburn in northwestern Montana resulted in a 25% duff depth reduction (original depth of 6.8 cm) and a loss of 100 kg N/ha, all from the surface organic layer. This represented 6% of the total pre-fire nitrogen in the surface 30 cm of the soil (Jurgensen *et al.* 1981). The authors felt there would be no long-term depletion of soil nitrogen reserves caused by this fire.

In Oregon, losses from burning ranged from 223-571 kg N/ha and losses from harvesting and burning ranged from 721-1142 kg N/ha (Little and Klock 1985). Two utilization standards were used in the study: the removal of all material greater than 10 cm in diameter x 120 cm in length, and all material greater than 15 cm x 180 cm. Reducing the amount of slash appeared to reduce the total amount of nitrogen lost from logging and burning (higher losses associated with logging were more than compensated for by lower losses associated with burning). If other factors are equal, a net saving of nitrogen may be made on units that are burned if they are logged to closer utilization standards.

In a coastal British Columbia study, total losses from the forest floor alone ranged from 216 kg N/ha for the lowest impact burn to 1328 kg N/ha for the highest impact burn.[1]

---

[1] Beese, W.J. [no date]. Summary of current research on soils and site productivity. MacMillan Bloedel Ltd., Nanaimo, B.C. Unpublished report.

On a mesic site in the SBS, there was a decrease in the concentration of forest floor N in four plots and an increase in two plots 9 months after a broadcast burn (Macadam 1987). In the mineral soil, there were variable and generally minor changes. Losses from the forest floor and mineral soil (to a depth of 30 cm) averaged 376 kg N/ha, representing 14% of the pre-fire soil nitrogen content. After 21 months, there was a slight increase in the forest floor nitrogen concentration and no change in the top 15 cm of the mineral soil.

In another SBS study, losses from slashburning amounted to 563 kg N/ha on mesic sites and 345 kg N/ha on subhygric/hygric sites (Taylor 1987). After low impact (slash load reduction of 6.81-7.28 kg/m^2) and moderate impact (slash load reduction of 9.57-11.38 kg/m^2) slashburns, Taylor and Feller (1986) concluded that the future availability of nitrogen may be of concern on mesic sites, but less so on subhygric/hygric sites.

In a third SBS study, Ballard and Hawkes (1989) reported that foliar nitrogen deficiencies tended to be more frequent and more severe on burned than on unburned sites, while tree growth was generally better.

In Montana, DeByle and Packer (1981) found that nitrogen in the surface organic horizon decreased from 60 g/m^2 pre-burn to 40 g/m^2 post-burn. This equates to a reduction of 200 kg N/ha. A year later, it had decreased to 36 g/m^2, a further reduction of 40 kg/ha. The nitrogen content in the mineral soil did not change after burning or in the subsequent year (nitrogen content was 1.0% in the surface 5 cm and 0.08% at 5-10 cm).

Jurgensen *et al.* (1981) reported that the ammonium concentration in the soil increased within 2 days of burning. After a 3-week delay, there was rapid nitrification (the oxidation of ammonium to nitrate) associated with a larger population of nitrifying bacteria. The time lag may have been caused by the inability of nitrifying microflora to compete with other soil micro-organisms for available ammonium (Jones and Richards 1977, cited by Jurgensen *et al.* 1981). The nitrate concentrations were very responsive to precipitation, and rapid declines in nitrate levels were probably caused by leaching associated with rainfall events.

In a 25-year study carried out west of the Cascade Range in Washington and Oregon, nitrogen had apparently been replenished through the decomposition of organic residues and the fixation of atmospheric nitrogen (Kraemer and Hermann 1979).

Carbon:nitrogen ratios usually had decreased in the forest floor and consistently had decreased in the mineral soil 9 months after burning (Macadam 1987). After 21 months, the C:N ratio had risen to or above pre-burn ratios in the forest floor and mineral soil, because of increases in total carbon.

In the 2-year study in Montana by Entry *et al.* (1987), the C:N ratios in organic horizons were usually not significantly different between a clearcut residue-burned plot and a clearcut residue-left plot. These ratios were significantly lower than those on either clearcut residue-removed or uncut control plots.

Several research projects have concentrated on the effects of underburning in ponderosa pine. Kovacic *et al.* (1986) found that soil ammonium and nitrate concentrations increased after burning, but that there was no significant difference in total soil nitrogen. Covington and Sackett (1986) found higher ammonium and nitrate concentrations on plots that were repeatedly burned (at 1-, 2-, and 4-year intervals) than on unburned controls. There was no significant difference in total nitrogen among treatments. The authors concluded that, on the site studied, frequent periodic burning can be used to enhance nitrogen availability.

After underburning in central Oregon, foliar nitrogen concentration did not change among the control and two intensities of burning plots (Landsberg *et al.* 1984). Height growth and basal area growth were both reduced after four seasons, with volume reductions of 23% on the burned plots as compared to the control. The reductions in growth may have been density-dependent and treatments in higher density stands may show improved growth.

Burning in mountain shrub and grassland communities in Colorado increased the rate of nitrogen mineralization (the process that produces ammonium from organic nitrogen compounds) (Hobbs and Schimel 1983). Most of this increase was attributed to increased soil temperature. However, repeated burnings may reduce the organic substrate and result in smaller microbial populations and poorer nutrient cycling.

There are two major sources of nitrogen found outside the forest ecosystem (Klock and Grier 1979). They are atmospheric inputs in precipitation (fallout), and the fixation of atmospheric dinitrogen. The latter is very important on sites where significant nitrogen volatilization occurs. Many species of *Alnus*, *Ceanothus*, *Purshia*, *Lupinus*, and *Shepherdia* harbour nitrogen-fixing symbionts in root nodules and can play an important role in fire-induced ecosystems. One study site in Idaho was reinvaded by *Ceanothus velutinus* after burning (Clayton and Kennedy 1985). Nitrogen fixation by *C. velutinus*, it was found, could replace total site nitrogen in approximately 20 years. Without burning, *C. velutinus* was less common and fixation rates were far lower.

3.2.2 Sulfur

In an Idaho study, losses of sulfur resulting from bole removal alone amounted to 22 kg/ha (5% of ecosystem sulfur) (Clayton and Kennedy 1985). In the short term, prescribed fire can improve sulfur availability through rapid mineralization (Curran and Dunsworth 1988). However, the total amount of sulfur on a site can be significantly reduced. Losses from burning averaged 87 kg total S/ha (56% of the pre-burn amount in slash and the forest floor) on mesic SBS sites and 74 kg total S/ha (14% of pre-burn amount) on subhygric/hygric SBS sites (Taylor 1987). The amount of sulfur volatilized is determined by the severity of the fire (Tiedemann 1987).

A large amount of sulfur can be lost through volatilization during a prescribed fire. When forest foliage and litter were burned in a laboratory experiment, 24-82% of the sulfur was volatilized at burning temperatures of 375-575°C for a period of five minutes (Tiedemann 1987). The extent of the losses depended on the species of vegetation, temperature, and duration of burn. At higher temperatures (775-1175°C), vegetation type makes little difference.

Because nitrogen can potentially be replaced by nitrogen-fixing species, sulfur losses may represent a more critical long-term effect of fire on forest productivity (Klock and Grier 1979). However, in Clayton and Kennedy's Idaho study (1985), it was estimated that the replacement of sulfur from precipitation inputs could be accomplished within 10 years.

3.2.3 Calcium

Calcium losses resulting from logging in southwestern Idaho amounted to 352 kg/ha (9% of the ecosystem calcium) (Clayton and Kennedy 1985). In the coastal British Columbia study by Feller and Kimmins (1984), it was determined that log export was the major pathway for calcium loss. It was estimated that, following logging, calcium could be replaced by inputs from precipitation alone over an 80-year rotation. However, following clearcutting and burning, it seems that precipitation inputs may be insufficient to replace fully the lost calcium.

In coastal British Columbia, slashburning resulted in an increase of 13 kg Ca/ha in the forest floor and a decrease of 100 kg Ca/ha from the slash, for a combined loss of 87 kg Ca/ha (Feller *et al.* 1983).

On a mesic SBS site, losses from burning averaged 252 kg total Ca/ha (40% of the pre-burn calcium in the slash and forest floor); on a subhygric/hygric site, losses averaged 289 kg total Ca/ha (6% of the pre-burn amount) (Taylor 1987).

In the SBS, 9 months after burning, the concentration of exchangeable calcium more than doubled in most cases within the forest floor (Macadam 1987). Even with the reduction in forest floor depth accounted for, there were still significant increases. Pre- and post-burn differences within the mineral soil (0-15 cm) were variable and not significantly different.

In a Montana study, 1 year after burning, calcium in the surface organic layer was reduced from 72 g/m² pre-burn to 66 g/m² (DeByle and Packer 1981). This difference, equating to 60 kg Ca/ha, was not statistically significant. Exchangeable calcium in the mineral soil did not show significant differences due to burning.

Taylor and Feller (1986) found an increase in exchangeable calcium in the mineral soil of mesic SBS sites, but no significant trend in subhygric/hygric SBS sites.

3.2.4 Magnesium

The primary pathway of magnesium losses is log export (Feller and Kimmins 1984), although losses from burning also occur. In Idaho, 29 kg Mg/ha (13% of the magnesium from the standing crop, litter, and soil pool) were lost through bole removal (Clayton and Kennedy 1985).

A slashburn in coastal British Columbia resulted in a decrease of 9 kg Mg/ha in the slash component and an increase of 2 kg Mg/ha in the forest floor, for a combined decrease of only 7 kg Mg/ha (Feller *et al.* 1983). Magnesium, one study found, could be replaced by inputs from precipitation alone over an 80-year rotation following clearcutting and burning (Feller and Kimmins 1984).

On mesic sites in the SBS, exchangeable magnesium increased an average of 75% within the forest floor 9 months after burning (Macadam 1987). Even accounting for the reduction in forest floor depth, magnesium content still increased substantially. The total amount of magnesium in the mineral soil (to a depth of 30 cm) remained close to pre-fire levels.

In western Montana, DeByle and Packer (1981) found a reduction in the surface organic horizon from 15.4 g Mg/m² before burning to 8 g Mg/m² 1 year after burning. This reduction was attributed to leaching, erosion, and plant uptake. There was a significant increase in exchangeable magnesium in the surface 10 cm of mineral soil 1 year after burning.

On a coastal Alaska site, there was no significant reduction in the organic horizon depth, but magnesium decreased significantly (from 0.288 to 0.145%) (Stednick *et al.* 1982). The lower levels in the organic horizon were reflected by higher concentrations in streamflow. The mineral soil was not sampled.

3.2.5 Potassium

In Idaho, bole removal resulted in potassium losses of 85 kg/ha or 21% of the ecosystem potassium (not including primary mineral or unavailable mineral potassium) (Clayton and Kennedy 1985). On a percentage basis, this was the largest loss of all nutrients studied (K, Ca, Mg, S, P, and N). Feller and Kimmins (1984) determined that potassium losses from log export on a coastal British Columbia site were greater than those from slashburning. Following logging, potassium replacement over an 80 year rotation would require inputs in precipitation and possibly from mineral weathering.

Losses as a result of slashburning in the CWH zone in coastal British Columbia amounted to 17 kg K/ha from the forest floor and slash (Feller *et al.* 1983). Of this, 27 kg K/ha was lost from the slash, while there was an increase of 10 kg K/ha in the forest floor.

Nine months after burning, on a mesic SBS site, exchangeable potassium in the forest floor decreased in four out of six plots (Macadam 1987). After compensating for the decrease in forest floor depth, potassium decreased by an average of one-third. Exchangeable potassium to a depth of 30 cm in the mineral soil remained close to pre-fire levels. After 21 months, further decreases occurred in the forest floor. Mineral soil (0-15 cm) was sampled at two plots 21 months after burning. Both had higher concentrations than at pre-burn levels.

In another SBS study, average losses from broadcast burning were 60 kg K/ha on mesic sites (40% of the pre-burn total in the slash and forest floor) and 16 kg K/ha on subhygric/hygric sites (5% of the pre-burn total) (Taylor 1987).

In Montana, DeByle and Packer (1981) found that potassium levels in the surface organic layer increased from 14.7 g/m² pre-burn to 19.6 g/m² post-burn (because of inputs from ash-fall), then decreased to 8.8 g/m² 1 year later. At 0-5 cm depth in the mineral soil, exchangeable potassium increased from 0.38 Meq/100g pre-burn to 0.47 Meq/100g 1 year post-burn. Increases of exchangeable potassium were evident to a depth of 30 cm.

Nissley *et al.* (1980) also found that potassium levels increased in the mineral soil, and commented that potassium appeared to be more mobile than calcium or magnesium.

3.2.6 Phosphorus

In Idaho, stem removal during logging removed 12 kg P/ha, which was equivalent to 5% of the total pool within the standing crop, litter, and soil (Clayton and Kennedy 1985). During logging and burning operations, log export was considered to be the major pathway for the loss of phosphorus (Feller and Kimmins 1984). To replace the phosphorus removed by logging alone would require inputs from precipitation and possibly from mineral weathering if total replacement were to occur over an 80-year rotation.

A slashburn in the coastal British Columbia CWH zone reduced the amount of phosphorus in the forest floor and slash by 8 kg/ha — a decrease of 14 kg/ha in the slash layer and an increase of 6 kg/ha in the forest floor (Feller *et al.* 1983).

Losses attributed to burning in the SBS averaged 55 kg P/ha (41% of the total P in the slash and forest floor) on mesic sites and 52 kg P/ha (13% of the total P) on subhygric/hygric sites (Taylor and Feller 1986). The future availability of phosphorus may be of concern on the former sites but not on the latter.

On a mesic SBS site, available phosphorus in the forest floor doubled and sometimes tripled following burning (Macadam 1987). Significant increases also occurred in the top 15 cm of the mineral soil (average pre-burn levels were 165 ppm compared to 228 ppm 9 months after burning). There were lesser increases or no change at the 15-30 cm depth. Available phosphorus in the forest floor and top 30 cm of mineral soil increased by 110 kg/ha after burning. Twenty-one months after burning, phosphorus decreased in some cases from the 9-month levels, but it was always above pre-burn levels.

In Montana, total phosphorus content rose from 5.6 g/m² pre-burn to 6.5 g/m² post-burn, probably as a result of ash-fall (DeByle and Packer 1981). During the following year, leaching and erosion reduced the phosphorus content to 4 g/m² (a reduction of 16 kg/ha from the pre-burn content). Over the same period, phosphorus content in the surface 5 cm of mineral soil rose from 78 to 84 ppm.

In Kraemer and Hermann's 25-year study (1979) in western Washington and Oregon, slashburning had no apparent long-term effect on phosphorus levels.

Following underburning in ponderosa pine, phosphorus content increased in the top 2 cm of mineral soil, but not in the 2-4 cm layer (Nissley *et al.* 1980).

3.2.7 Iron

Although iron is an essential micro-nutrient, few papers deal with the effects of slashburning on iron availability. Iron often occurs in insoluble forms. Its availability is enhanced by a variety of chelating agents, of which one group is known as hydroxymate siderophores (HS) (Perry *et al.* 1984). These chelators have a high affinity for Fe^{+3}. They are produced and secreted into the soil by various soil microflora, including mycorrhizal fungi.

Perry *et al.* (1984) found that HS concentrations were significantly lower in logged than unlogged areas. Furthermore, HS reductions were greater in burned than unburned areas. Limitations in iron supply in burned areas may be due to a reduction in HS producing organisms.

In the SBS, Ballard and Hawkes (1989) found that the active iron concentration in white spruce (*Picea glauca*) foliage tended to be less on burned than on unburned sites.

3.3 Soil Acidity

A decrease in soil acidity (increased pH) after burning can indirectly affect tree growth by affecting nutrient availability, and by increasing pH-dependent cation exchange capacity which in turn can increase nutrient retention. It is also important to note that the optimal pH for tree growth varies among species (Curran and Dunsworth 1988).

With one exception, all articles that monitored pH changes found an increase in pH after burning, although not all the increases were statistically significant.

The most dramatic pH changes occurred in the organic horizons. On a mesic site in the SBS, average pH increased from 3.6 pre-burn to 5.3 nine months after burning (Macadam 1987). In the mineral soil, there was a trend toward increased pH, but it was less than 0.5 unit. Taylor and Feller (1986) reported an increase in pH in the forest floor on mesic sites, but little effect on subhygric/hygric sites (although there was a trend towards higher pH after burning).

In Oregon, a higher severity burn appeared to result in a larger pH increase. An elevated pH was still evident 4 years after burning at the organic-mineral soil interface (Tarrant 1954). After a September broadcast burn in Montana, elevated pH levels were also evident in the humus layer 4 years after burning but, in the mineral horizons, pH returned to pre-burn levels by the following fall (Jurgensen *et al.* 1981).

The only exception to the trend of increasing pH after burning is reported by Stednick *et al.* (1982) in southeastern Alaska. Following burning, a statistically insignificant reduction from 4.45 to 4.14 in the litter horizon was reported.

3.4 Temperature

Mineral soil temperatures can increase significantly after burning. This can increase growth on colder sites, notably of spruce (Ballard and Hawkes 1989) and possibly of other species. The temperature differential between burned and unburned sites at 5 cm of depth can be 10°C or more, decreasing rapidly with depth and shading (Shearer 1974). Surface soil temperatures on blackened soils can be as much as 25°C higher than natural conditions.

Fowler and Helvey (1981) found that soils within a plot covered with wood chips had lower soil temperatures than did broadcast-burned, piled and burned, or scarified plots. For the first 2 years after burning on sites in Montana and Wyoming, the average maximum temperature was 5-9°C greater on a burned surface than on a litter surface (all residues greater than 2.5 cm were removed) (Hungerford and Babbitt 1987). After 2 years, brush provided sufficient shade on the burned area to reduce surface temperature below that of the litter surface. Mineral soil exposure resulted in lower maximum and higher minimum surface temperatures than occurred on burned or litter surfaces.

The wider temperature ranges found on freshly burned sites can lead to "hot events" (described by Hungerford and Babbitt [1987] as 2 or more consecutive hours of surface temperature greater than 122°F [50°C] or 1 hour at 133°F [56°C] or higher) and "cold events" (the occurrence of surface temperatures of 23°F [-5°C] or lower). These thresholds may not cause death, but they do represent a significant hazard to survival.

Hungerford and Babbitt (1987) compared different species' survival to hot events (HE) and cold events (CE). They found that the pattern of survival for ponderosa pine was better explained by CE's (lower survival corresponded with more CE's). For western larch, the frequency of HE's during the growing season better explained the survival trend (lower survival corresponded with more HE's). For Douglas-fir, HE's and CE's seemed to be about equal in explaining the trend. Ponderosa pine is better adapted to hot, dry sites and appears to survive HE's better than CE's. Western larch would be more sensitive to hot, dry sites so mortality is probably the result of HE's and related moisture stress before CE's occurred. Douglas-fir seemed to be somewhere in between and may be equally susceptible to HE's and CE's (Hungerford and Babbitt 1987).

Damage from heat events may result from direct heat injury or from high temperatures causing soil dessication and creating moisture stress. Cold events probably cause freezing of plant tissues (Hungerford and Babbitt 1987).

The rate of cellulose decomposition was much higher in burned sites, likely as a result of higher soil temperatures (Bissett and Parkinson 1980). Low soil temperature was concluded to be the major factor limiting microbial activity.

3.5 Post-burn Productivity

It is sometimes difficult to assess the effects of slashburning on site productivity. Not all effects are direct. For example, tree growth could be improved if fire reduces vegetation competition.

The increase in available nutrients immediately after a burn may improve growth conditions in the short term only, though the long-term effects are often unknown (Ballard 1986; Ballard and Hawkes 1989).

In young Douglas-fir plantations (5-15 years old) on dry salal-dominated ecosystems on eastern Vancouver Island (in the CWH), increased height growth and larger basal diameters were found more on burned than on unburned sites (Vihnanek 1985). Larger increases in height growth of planted Douglas-fir were more often associated with high and medium burn severities than with low burn severity (Vihnanek and Ballard 1988). It was not known if the improved growth trends would continue, but the risks of long-term losses in productivity were considered to be higher on severely burned sites (Vihnanek 1985). Also, on most sites, stocking of planted Douglas-fir was significantly higher on burned than unburned areas. It appears that this was due to differences in survival rather than differences in initial plantation density (Vihnanek and Ballard1988).

In coastal British Columbia, after two growing seasons, the volume growth of Douglas-fir, western redcedar, and yellow cypress was greater on burned than unburned sites. Shrub and herb growth was inversely related to the severity of the burn.[2]

In the interior of British Columbia, survival and growth of spruce seedlings in the first season after planting was better in burned than unburned ecosystems of both mesic and subhygric/hygric SBS sites (Taylor 1987). However, seedling foliar nitrogen and phosphorus concentrations were lower in burned areas. Ballard (1986) stated that lower foliar concentrations may be due to reduced nutrient uptake or to the dilution effect. Improved growth on burned sites may be the result of increased growing-season temperatures in the root zone, but the growth may also be less than the site's potential because of nutrient deficiencies.

4 CONCLUDING COMMENTS

Conclusions from different studies vary considerably depending on many factors: the amount and type of slash; fire weather indices; timing of logging, burning, and sampling; variations in data collected; and the ecological characteristics of the site. Slashburning may have beneficial or detrimental effects depending on the interactions among these and other variables.

Because of the complexity of burning, it is difficult to make general statements on how slashburning affects site productivity. Extrapolation of research results to operational settings must be done with caution as these results are often site-specific.

However, two conclusions seem to be consistent in the literature:

1. lower severity fires have a lower risk of causing site degradation than higher severity fires; and
2. at any given fire severity, drier nutrient-poor sites have a higher risk of being degraded than moister nutrient-rich sites.

Many authors also concluded that, under suitable conditions, burning would not cause significant site degradation. When conditions are not suitable, long-term losses in productivity could occur.

---

[2] Ibid.

5 LITERATURE CITED

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60(4):349-357.

Ballard, T.M. 1986. Slashburning effects on growth and nutrition of planted white spruce in interior British Columbia. *In* Fire Management Papers Submitted to the Fire Management Symp. Sponsored by the Central Interior Fire Protection Committee, Prince George, B.C. April 8-9, 1986, pp. 69-78.

Ballard, T.M. and B.C. Hawkes. 1989. Effects of burning and mechanical site preparation on growth and nutrition of planted white spruce. For. Can., Pac. For. Cent., Victoria, B.C. BC-X-309.

Beese, W.J. 1986. Effects of prescribed burning on some coastal B.C. sites. *In* Prescribed fire management issues, Northwest Forest Fire Council Annual Meet. Proc. - 1986, Nov. 18-19, 1986. Olympia, Wash.

Bissett, J. and D. Parkinson. 1980. Long-term effects of fire on the composition and activity of the soil microflora of a subalpine, coniferous forest. Can. J. Bot. 58:1704-1721.

Boyer, D.E. and J.D. Dell. 1980. Fire effects on Pacific Northwest soils. U.S. Dep. Agric. For. Serv., Pac. NW Reg. Manage. and Aviation and Fire Manage., Portland, Oreg.

Brown, J.K. and N.V. DeByle. 1987. Fire damage, mortality, and suckering in aspen. Can. J. For. Res. 17:1100-1109.

Clayton, J.L. and A.A. Kennedy. 1985. Nutrient losses from timber harvest in the Idaho batholith. Soil Sci. Soc. Am. 49:1041-1049.

Covington, W.W. and S.S. Sackett 1986. Effect of periodic burning on soil nitrogen concentrations in ponderosa pine. Soil Sci. Soc. Am. J. 50(2):452-457.

Curran, M.P. and B.G. Dunsworth. 1988. Coastal western red cedar regeneration: problems and potentials. *In* Proc. Conf. on Western Red Cedar — Does It Have a Future? July 13-14, 1987. N.J. Smith (editor). Fac. For., Univ. B.C., Vancouver, B.C., pp. 20-32.

DeBano, L.F. 1981. Water repellent soils: a-state-of-the-art. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. PSW-46.

DeBano, L.F. and J.S. Krammes. 1966. Water repellent soils and their relation to wildfire temperatures. Int. Assoc. Sci. Hydrol. Bull., XI Annee 2, pp. 14-19.

DeBell, D.S. and C.W. Ralston. 1970. Release of nitrogen by burning light forest fuels. Soil Sci. Soc. Am. Proc. 34:936-938.

DeByle, N.V. and P.E. Packer. 1981. Soils and Watershed. *In* Clearcutting and fire in the larch/Douglas-fir forests of western Montana: a multifaceted research summary. N.V. DeByle (editor). U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT- 99, pp. 47-52.

Durgin, P.B. 1985. Burning changes the erodibility of forest soils. J. Soil Water Conserv. 40(3):299-301.

Entry, J.A., N.M. Stark, and H. Loewenstein. 1987. Effect of timber harvesting on extractable nutrients in a northern Rocky Mountain forest soil. Can. J. For. Res. 17:735-739.

Feller, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. B.C. Min. For., Land Manage. Rep. No. 13.

_____ . 1988. Relationships between fuel properties and slashburning-induced nutrient losses. For. Sci. 34(4):998-1015.

Feller, M.C. and J.P. Kimmins. 1984. Effects of clearcutting and slashburning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. 20(1):29-40.

Feller, M.C., J.P. Kimmins, and K.M. Tsze. 1983. Nutrient losses to the atmosphere during slashburns in southwestern British Columbia. Paper presented at the 7th Conf. on Fire and Forest Meteorology. Am. Meteorol. Soc., Boston, Mass.

Fowler, W.B. and J.D. Helvey. 1981. Soil and air temperature and biomass after residue treatment. U.S. Dep. Agric. For. Serv., Res. Note PNW-383.

Gray, D.H. and W.F. Megahan. 1981. Forest vegetation removal and slope stability in the Idaho batholith. U.S. Dep. Agric. For. Serv., Res. Pap. INT-271.

Harvey, A.E., M.F. Jurgensen, M.J. Larsen, and J.A. Schlieter. 1986. Distribution of active ectomycorrhizal short roots in forest soils of the Inland Northwest: effects of site and disturbance. U.S. Dep. Agric. For. Serv., Res. Pap. INT-374.

Henderson, G.S. and D.L. Golding. 1983. The effect of slash burning on the water repellency of forest soils at Vancouver, British Columbia. Can. J. For. Res. 13:353-355.

Hobbs, N.T. and S.D. Schimel. 1983. Fire effects on nitrogen mineralization and fixation in mountain shrub and grassland communities. J. Range Manage. 37(5):402-405.

Hungerford, R.D. and R.E. Babbitt. 1987. Overstory removal and residue treatments affect soil surface, air, and soil temperature: implications for seedling survival. U.S. Dep. Agric. For. Serv., Res. Pap. INT-377.

Jones, J.M. and B.N. Richards. 1977. Effect of reforestation on turnover of ^{15}N - labelled nitrate and ammonium in relation to changes in soil microflora. Soil Biol. Biochem. 9:383-392. Cited in Jurgensen, M.F., A.E. Harvey, and M.J. Larsen 1981. Effects of prescribed fire on soil nitrogen levels in a cutover Douglas-fir/western larch forest. U.S. Dep. Agric. For. Serv., Res. Pap. INT-275.

Jurgensen, M.F., A.E. Harvey, and M.J. Larsen. 1981. Effects of prescribed fire on soil nitrogen levels in a cutover Douglas- fir/western larch forest. U.S. Dep. Agric. For. Serv., Res. Pap. INT-275.

Klock, G.O. and C.C. Grier. 1979. Effects of fire on the long-term maintenance of forest productivity. *In* Proc. Conf. on Forest Fertilization, Sept. 25-27, 1979. S.P. Gessel, R.M. Kenady, and W.A. Atkinson (editors). Seattle, Wash., pp. 247-250.

Kovacic, D.A., D.M. Seift, J.E. Ellis, and T.E. Hakonson. 1986. Immediate effects of prescribed burning on mineral soil nitrogen in ponderosa pine of New Mexico. Soil Sci. 141(1): 71-76.

Kraemer, J.F. and R. K. Hermann. 1979. Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade Mountains. For. Sci. 25(3):427-439.

Landsberg, J.D., P.H. Cochran, M.M. Finck, and R.E. Martin. 1984. Foliar nitrogen content and tree growth after prescribed fire in ponderosa pine. U.S. Dep. Agric. For. Serv., Res. Note PNW-412.

Little, S.N., F.R. Ward and D.V. Sandberg. 1982. Duff reduction caused by prescribed fire on areas logged to different management intensities. U.S. Dep. Agric. For. Serv., Res. Note PNW-397.

Little, S.N. and G.O. Klock. 1985. The influence of residue removal and prescribed fire on distributions of forest nutrients. U.S. Dep. Agric. For. Serv., Res. Pap. PNW-338.

Little, S.N. and J.L. Ohmann. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. For. Sci. 34(1):152-164.

Macadam, A.M. 1987. Effects of broadcast slash burning on fuels and soil chemical properties in the Sub-Boreal Spruce zone of central British Columbia. Can. J. For. Res. 17:1577-1584.

Martin, R.E. 1981. Prescribed burning techniques to maintain or improve soil productivity. *In* Proc. Workshop on Reforestation of Skeletal Soils. Nov. 17-19, 1981. S.D. Hobbs and O.T. Helgerson (editors), pp. 66-70.

Merseneau, R.C. and C.T. Dyrness. 1972. Accelerated mass wasting after logging and slashburning in western Oregon. J. Soil Water Conserv. 27(3):112-114.

Nissley, D.D., R.J. Zasoski, and R.E. Martin. 1980. Nutrient changes after prescribed surface burning of Oregon ponderosa pine stands. *In* Proc. 6th Conf. on Fire and For. Meteorology, Soc. Am. For., Bend, Oreg., pp. 214-219.

Perry, D.A., S.L. Rose, D. Pilz, and M.M. Schoenberger. 1984. Reduction of natural ferric iron chelators in disturbed forest soils. Soil Sci. Soc. Am. 48:379-382.

Shearer, R.C. 1974. Early establishment of conifers following broadcast burning in western larch/Douglas-fir forest. *In* Proc. Tall Timbers Fire Ecology Conf. Missoula, Mont., U.S. Dep. Agric. For. Serv., pp. 481-500.

Stark, N. 1982. Soil fertility after logging in the northern Rocky Mountains. Can. J. For. Res. 12:679-686.

Stednick, J.D., L.N. Tripp, and R.J. McDonald. 1982. Slash burning effects on soil and water chemistry in southeastern Alaska. J. Soil Water Conserv. 37:126-128.

Tarrant, R.F. 1954. Effects of slashburning on soil pH. U.S. Dep. Agric. For. Serv., Rep. No. 102.

_____ . 1956. Effects of slashburning on some soils of the Douglas-fir region. Soil Sci. Soc. Am. Proc. 20(3):408-411.

Taylor, S.W. 1987. Initial effects of slashburning on the nutrient status of two Sub-Boreal Spruce zone ecosystems. M.Sc. thesis. Univ. B.C., Vancouver, B.C.

Taylor, S.W. and M.C. Feller. 1986. Initial effects of slashburning on the nutrient status of Sub-Boreal Spruce zone ecosystems. *In* Proc. Symp. on Fire Management, Prince George, B.C. Sponsored by the Central Interior Fire Protection Committee, pp. 79-91.

Tiedemann, A.R. 1987. Combustion losses of sulfur from forest foliage and litter. For. Sci. 33(1):216-223.

Van Lear, D.H. and S.J. Danielovich. 1988. Soil movement after broadcast burning in the Southern Appalachians. South. J. Appl. For. 12(1):49-53.

Vihnanek, R.E. 1985. The effects of slashburning on the growth and nutrition of young Douglas-fir plantations in some dry, salal-dominated ecosystems. M.Sc. thesis. Univ. B.C., Vancouver, B.C.

Vihnanek, R.E. and T.M. Ballard. 1988. Slashburning effects on stocking, growth, and nutrition of young Douglas-fir plantations in salal-dominated ecosystems of eastern Vancouver Island. Can. J. For. Res. 18:718-722.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredriksen, E.C. Franklin, R.C. Froelich, and P.H. Dunn. 1979. Effects of fire on soil: a state-of-knowledge review. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-7.

Woodmansee, R.G. and L.S. Wallach. 1981. Effects of fire regimes on biogeochemical cycles. *In* Terrestrial nitrogen cycles. F.E. Clark and T. Rosswall (editors). Ecol. Bull. (Stockholm) 33:649-669.